Spaceborne Lidar Calibration From Cirrus and Molecular Backscatter Returns

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***Abstract*—In order to make optimal quantitative use of multiwavelength spaceborne lidar data, it is essential that the lidar be well calibrated. Due to system gain/efficiency changes that can be expected to occur during the course of a shuttle or satellite mission, it is essential to employ a calibration approach that can be implemented on-orbit, preferably repeatable at least a few times per orbit. For wavelengths less than about 550 nm, *in situ* calibration can be accomplished via normalization to high-altitude nearly molecular scattering regions. However, for longer wavelengths beyond about 800 nm, particularly the popular Nd: YAG fundamental wavelength at 1064 nm, the Rayleigh normalization approach becomes questionable due to both an inherently weaker signal and a stronger, variable, and somewhat unknown aerosol scattering contribution. For lidars operating at both longer and shorter wavelengths, a viable approach is to retrieve the longer wavelength calibrations ratioed to the shorter wavelength calibrations via comparisons of spectral backscatter from known/quantifiable scatterers. Cirrus clouds are good for this purpose because they occur at high altitudes with significant frequency and provide strong nearly spectrally flat backscatter. This paper presents both the molecular normalization and cirrus spectral backscatter ratio calibration approaches, including results obtained from case studies of lidar data collected during the LITE shuttle mission. Attention is focused on developing a simple autonomous approach applicable to satellite lidar missions such as Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) and the Geoscience Laser Altimeter System (GLAS).**

***Index Terms*—Cirrus backscatter, Lidar callibration, spaceborne Lidar.**

I. Introduction

CLOUD-AEROSOL Lidar Infrared Pathfinder Satellite Observations (CALIPSO) (formally referred to as PICASSO-CENA [1]) is a recently approved mission within the National Aeronautic and Space Administration's (NASA) Earth System Science Pathfinder (ESSP) program that will obtain new measurements of clouds and aerosols to improve predictions and the impact of climate change. This mission is being developed as a partnership between NASA and the French space agency CNES and is planned for launch in early 2004. The CALIPSO payload consists of a two-wavelength (532 nm and 1064 nm) polarization-sensitive (for 532 nm) lidar and two coaligned passive instruments. Data from these three instruments will be used to measure the vertical distributions of aerosols and clouds in the atmosphere, as well as optical and physical properties of aerosols and clouds, that influence the earth's radiation budget. The Geoscience Laser Altimeter System (GLAS) laser altimeter to be carried on ICESat (one of NASA's Earth Observing System satellites planned for launch at the end of 2002 or early 2003), which has the primary task of measuring ice-sheet topography, also features a two-wavelength atmospheric lidar [2]. Calibration of these satellite lidars is essential in order to achieve quantitative retrievals of aerosol and cloud properties.

Following the procedures employed for the Lidar In-Space Technology Experiment (LITE), *in situ* calibration of the 532-nm lidar channel can be accomplished via normalization to a high-altitude nearly molecular scattering region. However, the molecular backscatter is too weak to permit such calibration for the longer 1064-nm channel. An alternative approach investigated in [3] during the LITE shuttle mission [4] employed surface backscatter returns from selected land surfaces as standard targets to calibrate the LITE 1064-nm channel. This approach yielded calibration uncertainties in the 10% range, but only for limited well-characterized surfaces. During the course of a satellite mission, a more desirable calibration approach is one that can be implemented on-orbit, preferably repeatable at least a few times per orbit. With this objective, a new 1064-nm calibration method is proposed in this paper, specifically that the calibration of the 1064-nm channel relative to the 532-nm channel calibration be accomplished via comparisons of the 532- and 1064-nm backscatter signals from cirrus clouds. Due to the low signal for noncloud returns, it is difficult to remove the noncloud signal from the total signal. For the approach presented here, only strong cloud signal returns are selected. Consequently, the contamination by noncloud returns is minimized. This avoids uncertainty in subtracting a variable background level that must be done for weak cloud returns.

Examples demonstrating the 532-nm molecular normalization calibration approach are presented based on representative LITE data from orbits 24 and 34. Error assessments are included that support achievable calibration uncertainties within 5% by this approach. Cirrus cloud returns from LITE orbits 23, 24, and 27 have been analyzed to assess the feasibility of the cirrus cloud calibration approach. Results are given which indicate that calibration of the CALIPSO 1064-nm channel in terms of, or as a ratio to, the 532-nm calibration factor by using cirrus cloud returns appears quite feasible.

II. Physical Model and Mathmatical Description

Calibration of a nadir/near-nadir viewing spaceborne lidar via normalization to high-altitude nearly molecular scattering

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regions is, in principle, very straightforward [3]. The lidar calibration factor or constant, C, appears in the lidar equation and normalized equation as follows (e.g., [5], [6]):

$$P(r) = \frac{E_0 C \beta(r) T^2(r)}{r^2} \tag{1}$$

$$X(r) = \frac{r^2 P(r)}{E_0} \tag{2}$$

where

- E_0 transmitted laser pulse energy;
- r range or distance from the lidar to the point of scattering;
- $P(r)$ instantaneous lidar signal from range r;
- $\beta(r)$ atmospheric backscatter coefficient ($m^{-1} sr^{-1}$);
- $T(r)$ atmospheric transmittance through range r.

The calibration constant for 532 nm may be extracted from the lidar signal $P(r_c)$ obtained at a reference calibration range r_c by

$$C_{532} = \frac{r_c^2 P(r_c)}{R(r_c)\beta_m(r_c)T^2(r_c)E_0} = \frac{X(r_c)}{R(r_c)\beta_m(r_c)T^2(r_c)} \tag{3}$$

where, in addition to the terms defined above,

- $\beta_m(r_c)$ molecular (Rayleigh) atmospheric backscatter (for the lidar wavelength) at range r_c for 532 nm;
- $R(r_c)$ $\beta(r_c)/\beta_m(r_c)$; total-to-molecular backscattering mixing ratio at range r_c

For r_c selected to be around 30 km above ground, $R(r_c) \approx 1$ and $T^2(r_c) \approx 0.99$ are very good approximations for 532 nm, enabling accurate retrievals of C_{532}, providing that the signal uncertainty is sufficiently small and that $\beta_m(r_c)$ can be accurately computed (driven by how accurately the air density can be determined).

The total Rayleigh-scattering cross section per molecule σ is given by [7], [8]

$$\sigma(\lambda) = \frac{24\pi^3 (n_s^2 - 1)^2}{\lambda^4 N_s^2 (n_s^2 + 2)^2} \left(\frac{6 + 3\rho_n}{6 - 7\rho_n} \right) \tag{4}$$

where λ is the wavelength (in centimeters); n_s is the refractive index for standard air at λ; N_s is the molecular number density for standard air; and ρ_n is the depolarization factor, a term that accounts for the anisotropy of the air molecule and which varies with wavelength. The total molecular volume backscattering coefficient $\beta_{m,\lambda}(z)$ is given by the product of the total Rayleigh cross section per molecule σ as defined in (4), the molecular number density $N(z)$, for a given pressure and temperature at altitude z, and the Rayleigh extinction-to-backscatter ratio S_R (e.g., see [6] and [9])

$$\beta_{m,\lambda}(z) = S_R^{-1} N(z) \sigma(\lambda) \tag{5}$$

where $S_R = 8\pi/3$.

The Rayleigh-per-molecule cross section can be accurately determined within a few tenths of a percent [7], leaving $N(z)$ as the primary source of uncertainty in determining $\beta_{m,}\lambda(z)$. Using ancillary meteorological data along the satellite track, it is estimated that $\beta_m(r_c)$ can be determined within about $\pm 3\%$ uncertainty. For z near 30 km, this corresponds to knowing temperature within $\sim \pm 5$ K and pressure within $\sim \pm 2.5$ mb, which is about the level of uncertainty associated with just assuming a latitudinal, seasonal standard atmospheric model [5], [8]. Using pressure and temperature fields derived from weather network measurements and assimilation models, coupled with averaging the C_{532} retrievals over significant horizontal extents (~several hundred kilometers), it is anticipated that the $N(z)$ uncertainty can be further reduced. However, for the estimates presented here, it is assumed that $\beta_m(r_c)$ is not known better than $\pm 3\%$.

Given C_{532} determined by the molecular calibration approach, cirrus clouds offer good candidate targets by which the calibration ratio C_{1064}/C_{532} can be estimated from the ratio of the normalized returns for the two wavelengths. This is feasible because, to first order, the backscatter and extinction from cirrus should be nearly the same for both wavelengths. Also, as cirrus clouds occur at high altitudes, corrections for 1064/532 spectral transmittance differences between the satellite and the cloud top are relatively small and predictable.

The normalized cloud return $X_c(r)$, which is defined as the total normalized return minus the noncloud background normalized return, is given approximately by

$$X_c(r) = C_{1064} T_{ct}^2 \beta_c(r) T_c^2(r) \tag{6}$$

where

- C_{1064} lidar calibration factor;
- T_{ct}^2 round-trip transmittance to cloud top at range r_{ct};
- $\beta_c(r)$ cloud backscatter for $r > r_{ct}$;
- $T_c^2(r)$ cloud round-trip transmittance from r_{ct} to $r > r_{ct}$.

As cirrus particles are typically sufficiently large relative to the 532- and 1064-nm wavelengths for the geometrical optics limit to reasonably apply, there should be no wavelength dependence in the extinction and backscatter for these two wavelengths [10], [11], save any small refractive index difference effects. In addition, cirrus spectral optical depths measured by sunphotometers are observed to be quite spectrally flat over the $\sim$500-nm to the $\sim$1000-nm range [12]. In fact, screening for spectral flatness in optical depth is a technique often employed to detect the presence of very thin cirrus contamination in derived aerosol optical depths. Lidar data, though sparse, supports $\beta_{c,532} = \beta_{c,1064}$ within measurement/calibration uncertainties (albeit, these uncertainties are typically somewhat large, $\sim$10%–20%). Preliminary analysis of lidar observations made during the SAFARI-2000 campaign with the NASA/GSFC Cloud Physics Lidar, deployed on a NASA ER-2, reveals that $\beta_{c,1064}/\beta_{c,532}$ is quite constant, not highly variable, and close to unity [13]. Finally, for spaceborne lidar to cloud geometry and even a very small receiver field of view ($\sim$100 μrad), multiple scattering effects should be effectively the same for both wavelengths. All of this supports assuming $\beta_c T_c^2$ to be spectrally flat.

Assuming $\beta_c T_c^2$ is the same for 532 nm and 1064 nm, the ratio of X_c for the two wavelengths at any r within the cloud will be

$$\frac{X_{c1064}}{X_{c532}} = \frac{C_{1064}}{C_{532}} \times \frac{T_{ct1064}^2}{T_{ct532}^2} \tag{7}$$

yielding

$$\frac{C_{1064}}{C_{532}} = \frac{X_{c1064}}{X_{c532}} \times \frac{T^2_{cT532}}{T^2_{ct1064}}. \tag{8}$$

In order to minimize the noncloud return, a threshold is selected to screen out the weak backscatter signals. By setting a high threshold, the noncloud background can be ignored, allowing X_c to be approximated by X, the total signal including the noncloud background. Thus, the calibration ratio is given approximately by

$$\frac{C_{1064}}{C_{532}} \approx \frac{X_{1064}}{X_{532}} \times \frac{T^2_{ct,532}}{T^2_{ct,1064}}. \tag{9}$$

The last term is approximately 0.9 at about 12 km above ground and can be estimated from models of aerosol extinction and ozone concentration and an atmospheric density profile [8].

A threshold signal X_t for determining strong cloud returns may be determined by computing the 532-nm normalized signal that is equivalent to a scattering ratio of R_t.

Expressing $X_t(r)$ in terms of altitude above ground, z, which is normally how molecular and aerosol scattering coefficients and cloud positions are height referenced, $X_t(z)$ may be expressed by

$$X_t(z) = C_{532} \times R_t \times \beta_{m,532}(z) \times T^2_{532}(z_L - z) \tag{10}$$

where $R_t = (\beta_a(z) + \beta_m(z))/(\beta_m(z))$; z is the observation altitude above ground; and z_L is the lidar height above ground (i.e., r and z are related by $r = z_L - z$).

Setting R_t to a large value, on the order of 50, insures $X_c \approx X$. Once again, for the heights of cirrus clouds, the transmission term can be modeled accurately and is close to unity. This threshold is applied only to the 532-nm signals for determining cloud segments of sufficient signal intensity to be used for retrieving the calibration ratio.

III. Results and Discussion

A. Retrieval Results for the 532-nm Calibration Factor

Extracting absolute estimates of C_{532}, as can be seen from (3), requires that r_c, E_0, $R_{532}(r_c)$, $\beta_{m,532}(r_c)$, and $T^2_{532}(r_c)$ all be known/specified. It is assumed that this can be done with essentially no significant error (i.e., less than $\sim$ 0.5% error) for r_c and E_0 (a relative energy normalization is all that is actually required), and with manageably small error for $\beta_{m,532}(r_c)$, using temperature and pressure meteorological data incorporated in the CALIPSO database. As discussed earlier, using molecular number densities calculated from pressure and temperature fields derived from assimilated network measurements should yield estimates of $\beta_{m,532}(r_c)$, easily within $\pm 3\%$. Also, for r_c selected in the mid to upper stratosphere, $T^2_{532}(r_c)$ will generally be within about 1% of unity, but must still be specified to extract C_{532}.

In Fig. 1, retrievals of C_{532} from orbit 34 LITE data are presented for 4-km vertical averaging over the altitude range $z = 30$ to 34 km and 200-shot ($\sim$ 150 km) minimum horizontal block averaging, for various total horizontal extents of $\sim$ 1000 km up to half an orbit. In Fig. 1(a), C_{532} is calculated based on a 200-shot average spanning about a 1000-km total horizontal extent (during the nighttime portion). Fig. 1(b)

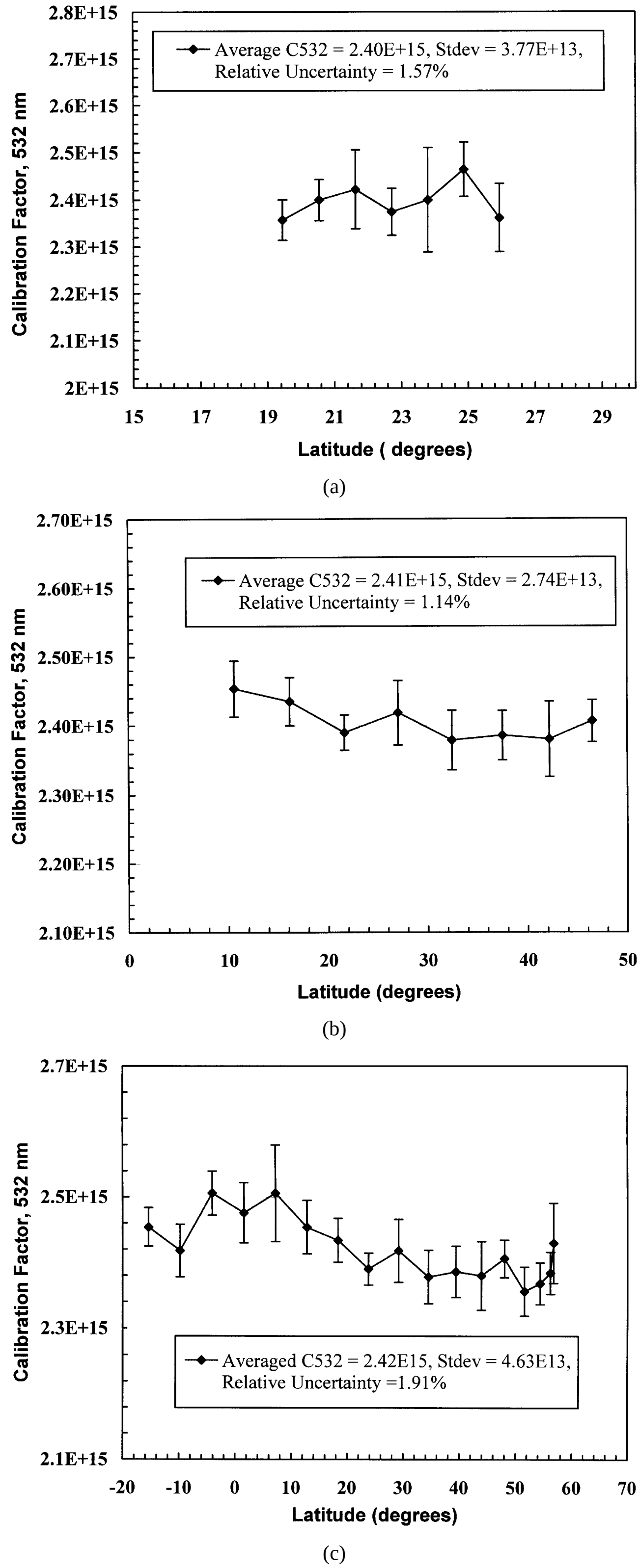


Fig. 1. Retrieved 532-nm calibration constant for portions of LITE orbit 34. (a) Based on a 200-shot average spanning about a 1000-km horizontal extent. (b) Based on a 1000-shot horizontal average over about half the nighttime portion of orbit 34. (c) Based on a 1000-shot horizontal average for the entire nighttime portion of orbit 34.

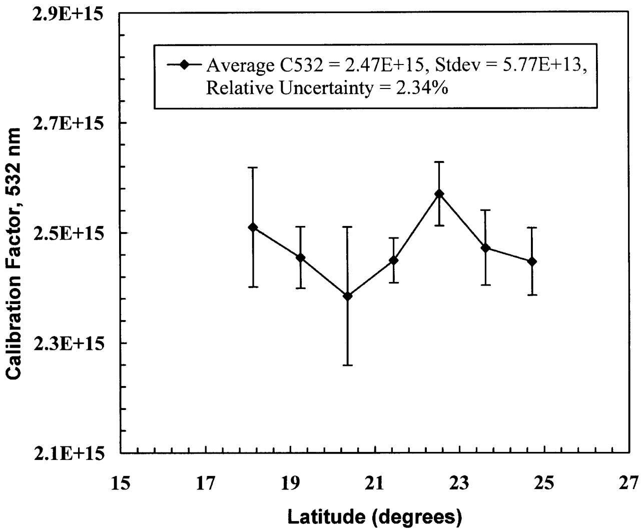


Fig. 2. Retrieved 532-nm calibration constant for a portion of LITE orbit 24 based on a 200-shot average spanning about a 1000-km horizontal extent.

is based on a 1000-shot average, spanning about half the nighttime portion of the orbit, and in Fig. 1(c), the 1000-shot average extends over the entire nighttime portion of the orbit. Each data point in Fig. 1(a)–(c) includes ± 1 standard deviation error bar for the number of shots averaged for the point (either 200 or 1000 shots). These values are averaged for the number of points in each figure, yielding the average and standard derivation values cited in the figures. The standard deviation of the 200-shot average points is mainly determined by the uncertainty in the normalized signal X and is in the range of 3%.

From Fig. 1, it can be seen that C_{532} for orbit 34 is around 2.41×10^{15}, and the relative uncertainty of C_{532} is less than 2%. Here it is important to note that these figures depict the effects of signal uncertainty and relative spatial variability in $\beta_{m,532}(r_c)$, $R_{532}(r_c)$, and $T_{532}^2(r_c)$, but not the absolute errors in these latter three factors. What the figures demonstrate is that averaging over horizontal extents of ~1000–10 000 km should still yield averages with uncertainties within about 2% insofar as these horizontal inhomogeneity effects are concerned. The results shown for orbit 34 are typical of other orbits [14], another example of which is shown in Fig. 2 for a segment of orbit 24, yielding a C_{532} within about 2% of the orbit 34 results. Some change in C_{532} between several orbits was observed during the LITE mission [14], presumably reflecting instrument changes and drift. Hence, a repeatable on-orbit calibration approach is needed to overcome these effects.

Applying standard error propagation analysis to the C_{532} retrieval equation (2) yields

$$\left[\frac{\delta C_{532}}{C_{532}}\right]^2 = \left[\frac{\delta X_{532}(r_c)}{X_{532}(r_c)}\right]^2 + \left[\frac{\delta R_{532}(r_c)}{R_{532}(r_c)}\right]^2 + \left[\frac{\delta \beta_{m,532}(r_c)}{\beta_{m,532}(r_c)}\right]^2 + \left[\frac{\delta T_{532}^2(r_c)}{T_{532}^2(r_c)}\right]^2. \quad (11)$$

Assuming uncertainties that should reasonably apply in the stratosphere for r_c in the range of 30–34 km above ground, as listed in Table I, yields an uncertainty in C_{532} of about 4.4% as also given in Table I.

TABLE I
THE UNCERTAINTY ESTIMATES OF THE 532-nm CALIBRATION CONSTANT AND RELATED PARAMETERS

$\frac{\delta C_{532}}{C_{532}}$	$\frac{\delta X_{532}}{X_{532}}$	$\frac{\delta R_{532}(r_c)}{R_{532}(r_c)}$	$\frac{\delta \beta_{m,532}(r_c)}{\beta_{m,532}(r_c)}$	$\frac{\delta T_{532}^2(r_c)}{T_{532}^2(r_c)}$
0.044	0.03	0.01	0.03	0.005

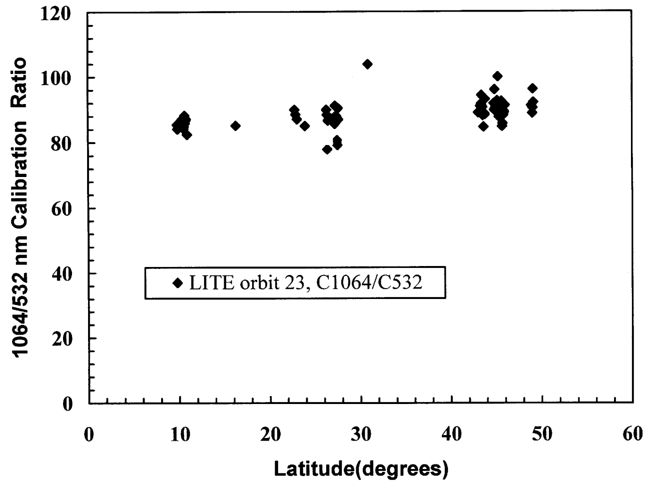
TABLE II
SUMMARY OF CALIPSO LIDAR PARAMETERS

Orbit Height	705 Km
Laser	Nd: YAG with ~110 mJ at 532 and 1064 nm
Polarization	532 nm has parallel and perpendicular channels
Laser Repetition Rate	20.25 Hz
Receiver Telescope Diameter	1.0 m
Vertical Resolution	30m - 300m, depending on altitude and wavelength
Horizontal Resolution	1/3 km - 5 km, depending on altitude

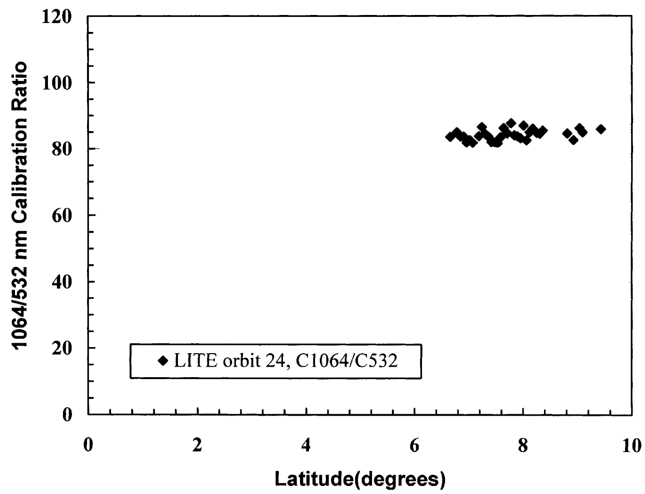
CALIPSO simulations based on specified lidar system parameters (summary of key parameters listed in Table II) predict that the shot-noise-limited uncertainty in $X(r)$ for a height of 30 km above ground and 4-km vertical averaging should be within about $\pm 3\%$ for horizontal averaging of not more than $\sim$ 1000 km. As shown in Figs. 1 and 2, results from LITE demonstrate that horizontal averaging over 1000 km and more without significant horizontal inhomogeneity biases is quite feasible. Hence, the molecular normalization approach should enable on-orbit calibrations of C_{532} for CALIPSO with uncertainties within $\pm 5\%$.

B. Retrieval Results for the C_{1064}/C_{532} Calibration Ratio

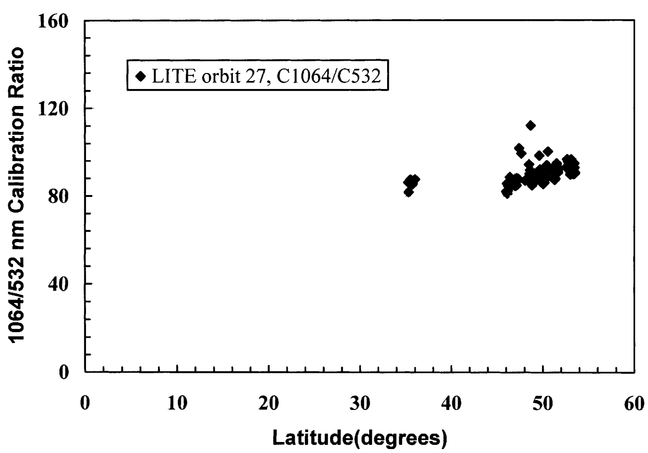
The C_{1064}/C_{532} calibration ratio retrieval approach outlined in Section II was applied using LITE data for the nighttime portions of orbits 23, 24, and 27. The search for cloud returns was restricted to the altitude region from 8–17 km above ground. This helps eliminate noncirrus cloud returns and facilitates the modeling of transmission terms in the retrieval equations. The screening threshold level R_t was set to 50, insuring strong cloud returns, permitting minimal horizontal averaging on only 10 shots ($\sim$ 7 km horizontal extent) to still yield a signal uncertainty typically within about $\pm 2\%$. Also, only the highest altitude cloud with a thickness (as determined by the threshold signal) of at least 180 m was used for each 10-shot average. Fig. 3 shows the relationship between the retrieved calibration ratio C_{1064}/C_{532} and the latitudes spanned by an orbit, corresponding to orbits 23, 24, and 27, respectively. For orbit 23, 61 cloud profiles (each set being a 10-shot average) met the signal selection requirements specified for the retrievals. For orbits 24 and 27, 29 and 111 cloud profile sets, respectively, were used for retrievals. There appears to be slightly greater scatter in the points for higher latitudes. This may be due to some mixed-phase/water clouds being present at higher latitudes within the altitude screening range (8–17 km) that was used to select cirrus



(a)



(b)



(c)

Fig. 3. Retrieved 1064/532 calibration ratios from selected cirrus cloud returns for (a) orbit 23, (b) orbit 24, and (c) orbit 27.

clouds. However, this variability does not appear to be statistically significant. The numerical results (means and standard deviations) for the C_{1064}/C_{532} calibration ratio retrievals are listed in Table III.

From Table III, it can be seen that the calibration ratio for the three nearly adjacent LITE orbits 23, 24, and 27 is very consistent with small standard deviations within $\pm 3\%$. In addition, the calibration ratio of these orbits agrees with the calibration ratio obtained from LITE ground reflections over Edwards dry lake bed (during orbit 24) within uncertainties for the ground reflection calibration retrieval [3]. The calibration ratio C_{1064}/C_{532} obtained at Edwards Air Force Base, CA was about 79 ± 8.

TABLE III
CALIBRATION RATIO C_{1064}/C_{532} FOR LITE ORBITS 23, 24, AND 27

Orbit	Calibration Ratio C_{1064}/C_{532}	Number of Cloud Profiles
23	88.1 ± 2.3	61
24	85.3 ± 1.5	29
27	88.5 ± 2.6	111

C. *Retrieval Uncertainty Estimates for the Cirrus Cloud C_{1064}/C_{532} Calibration Approach*

Assuming the current parameters for CALIPSO, the expected signal-to-noise ratio (SNR) for single-shot returns at about 11 km above ground from cirrus clouds with backscatter 50 times greater than 532-nm molecular backscatter, for a 180-m vertical range bin, is SNR ≈ 5 for both 532 nm and 1064 nm. Averaging over 5 km (15 shots) horizontally should yield an SNR of about 20, or a signal uncertainty (1/SNR) of about 5%, which reduces the signal uncertainty to a small enough level to apply fairly stringent statistical discriminants to reject "contaminated" or "atypical" horizontal cirrus cloud segments. Averaging over additional horizontal segments and/or vertical range bins should further reduce signal uncertainties as demonstrated by the LITE examples.

Including the possibility of some difference between βT^2 for 532 nm and 1064 nm within the cloud ($r > r_{ct}$), the ratio of the calibration constants may be expressed as

$$\frac{C_{1064}}{C_{532}} = \frac{X_{1064}}{X_{532}} \times \frac{T^2_{ct,532}}{T^2_{ct,1064}} \times \chi' \tag{12}$$

where

$$\chi' = \frac{\beta_{532}}{\beta_{1064}} \times \frac{T^2_{r>ct,532}}{T^2_{r>ct,1064}} \tag{13}$$

and

β_λ total cloud and noncloud backscatter;
$T^2_{r>ct,\lambda}$ total two-way transmittance from r to $r > r_{ct}$.

Applying standard error propagation analysis to (12), the relative uncertainty in C_{1064} can be expressed as

$$\left[\frac{\delta C_{1064}}{C_{1064}}\right]^2 = \left[\frac{\delta X_{1064}}{X_{1064}}\right]^2 + \left[\frac{\delta X_{532}}{X_{532}}\right]^2 + \left[\frac{\delta T^2_{ct,532}}{T^2_{ct,532}}\right]^2 + \left[\frac{\delta T^2_{ct,1064}}{T^2_{ct,1064}}\right]^2 + \left[\frac{\delta C_{532}}{C_{532}}\right]^2 + \left[\frac{\delta \chi'}{\chi'}\right]^2. \tag{14}$$

Conservative estimates for the error terms in (14) are given in Table IV, along with the resulting error in C_{1064}. Hence, it appears quite feasible to determine C_{1064} within $\pm 10\%$ using the

TABLE IV
UNCERTANINTY ESTIMATES OF THE 1064-nm CALIBRATION CONSTANT AND RELATED PARAMETERS

$\frac{\delta C_{1064}}{C_{1064}}$	$\frac{\delta X_{1064}}{X_{1064}}$	$\frac{\delta T^2_{ct,532}}{T^2_{ct,532}}$	$\frac{\delta X_{532}}{X_{532}}$	$\frac{\delta T^2_{ct,1064}}{T^2_{ct,1064}}$	$\frac{\delta C_{532}}{C_{532}}$	$\frac{\delta \chi'}{\chi'}$
0.097	0.05	0.02	0.05	0.002	0.05	0.04

cirrus cloud ratio approach. Given the ratio results from the LITE data analysis, it is anticipated that the C_{1064} calibration uncertainty that can be achieved for CALIPSO may more likely be less than $\pm 10\%$.

IV. SUMMARY AND CONCLUSION

Techniques have been presented for on-orbit calibration of spaceborne lidar applicable for both shorter visible wavelengths, such as 532 nm, and longer near-infrared wavelengths, such as 1064 nm. The approach for shorter wavelengths employs molecular (Rayleigh) scattering normalization at high altitudes ($\sim$ 30 km), while the approach for longer wavelengths determines the ratio of the longer-to-shorter wavelength calibration factors from selected cirrus cloud backscatter returns. These approaches have been demonstrated using example data from the LITE shuttle mission, including assessment of uncertainties.

Results presented here show that calibration of the CALIPSO 532-nm channel by molecular normalization, analogous to what was done for the LITE shuttle mission, is quite feasible and should yield calibrations with uncertainties of $\pm 5\%$ or less. Calibration of the CALIPSO 1064-nm channel in terms of, or as a ratio to, the 532-nm calibration factor by using cirrus cloud returns also appears quite feasible. The accuracy with which this can be achieved should conservatively be $\pm 10\%$ or less by selecting strong signal returns from cirrus clouds.

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